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Analytical and Experimental
Investigations of the Fracture
Mechanisms of Controlled
Polyphase Alloys

May 31, 1963

Prepared under Navy, Bureau of Naval Weapons

Contract N600(19)59361

Quarterly Progress Report No. 2

Period: January 30, 1963 through April 29, 1963

REPORTED BY J. A. Ford
J. A. Ford

R. W. Hertzberg
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SUMMARY

The results of continued investigations on selected unidirectionally solidified binary eutectic alloys are reported in this quarterly progress report. Large grains have been produced in the Al-$CuAl_2$ eutectic ingots. Microbend specimens, whose length dimension made an angle of zero, thirty, forty-five, sixty, and ninety degrees to the lamellae orientation, were prepared and tests carried out for the zero and ninety degree orientations indicated average tensile strengths of 46,800 psi and 22,900 psi, respectively. The failure mechanism(s) are characterized by Al platelet plastic deformation and by $CuAl_2$ platelet cleavage.

Preliminary information on the effect of Cr whisker orientation on the fracture mechanism(s) of unidirectionally solidified Cu-Cr ingots has been obtained for the case of whiskers oriented at 45° to the tensile load axis. The predominant failure mode was of the shear type. Also, the fracture mode of specimens solidified at high growth rates and tested parallel to the fiber orientation has been determined to be controlled by Cr whisker failure. Both shear and tensile failure modes have been identified.

Extensive examination has revealed that the shoulder failures in the Al-Al_3Ni controlled ingots were not due to microstructural peculiarities, but more probably to stress concentrations and/or load eccentricity. The Al_3Ni whiskers have been successfully extracted from the Al-matrix using a 5% aqueous HCl solution.

Analytical and Experimental Investigations of the Fracture Mechanisms of Controlled Polyphase Alloys

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Analytical and Experimental Investigations of the Fracture Mechanisms of Controlled Polyphase Alloys

INTRODUCTION

This is the second quarterly progress report for Contract No. N600(19)59361 entitled "Analytical and Experimental Investigations of the Fracture Mechanisms of Controlled Polyphase Alloys," covering the period from January 30, 1963 through April 29, 1963. The objective of this investigation is to determine the role of highly oriented fibrous and lamellar second-phase particles on the mechanical properties of selected eutectic alloys.

This report contains a brief description of results of the experimental work carried out during the second quarter and of the work to be conducted during the next report period.

CONTROLLED SOLIDIFICATION PROCEDURE

Al-$CuAl_2$ System

Several master heats of high-purity Al and Cu (99.999) were prepared by induction melting in $1\frac{1}{2}$-in. dia graphite crucibles. These master heats were then unidirectionally solidified in a newly designed high thermal-mass resistance furnace at a rate of 2.05 cm/hr. This experimental procedure was utilized in order to eliminate both the colony and banding defects.

MECHANICAL TESTING PROCEDURE

Continued tensile tests of unidirectionally solidified Cu-Cr ingots have been made and Al_3Ni whiskers have been extracted from unidirectionally solidified Al-Al_3Ni ingots for testing.

Cu-Cr System

Substandard tensile specimens (0.125-in. dia) were machined at an angle of 45° to the growth direction from a $1\frac{1}{2}$-in. dia Cu-Cr ingot grown at 1.28 cm/hr. These specimens were tensile tested at strain rates of 0.03 in./in./min.

Al-Al_3Ni System

The Al_3Ni whiskers have been successfully extracted from the Al-Al_3Ni unidirectionally solidified ingots using a 5% aqueous HCl solution. The extraction procedure must be carefully controlled in order to remove the whiskers without any damage. Some whisker surface attack by the extraction reagent will occur if the concentration of the HCl is allowed to increase to 15%. These extracted Al_3Ni whiskers will be tensile tested using the procedure outlined in the first progress report.

RESULTS AND DISCUSSION

Controlled Solidification Experiments

Al-$CuAl_2$ System

The banding problem discussed in the first progress report has been successfully eliminated by using a high thermal-mass resistance furnace as a heat source which does not produce significant temperature fluctuations in the melt. Using this technique, several $1\frac{1}{2}$-in. dia ingots were grown at 2.05 cm/hr. Large grains were produced in which no extensive banding occurred for over an inch in length which permitted machining of single-grain specimens for the microbend tests. Figure 1 compares an as-cast ingot cross-section to a unidirectionally solidified cross-section in which a single eutectic grain of $1\frac{1}{2}$-in. length was produced.

Mechanical Test Results

Cu-Cr System

Further tensile tests were performed on specimens solidified at both slow and fast growth rates. The test bars solidified at slow growth rates failed by a single shear mode and those solidified at fast growth rates failed by a mixture of tensile and shear modes, respectively, as discussed in the first progress report. The shear mode found in both specimen groups has already been associated

with the presence of "elongated dimples" induced by the fracture of Cr fibers (Ref. 1). Studies of the tensile failure mode revealed a fibrous fracture surface apparently caused by large amounts of plastic deformation. If the Cr fibers were still the controlling factor in fracture nucleation, the fibrous regions might reveal "equiaxed dimples" as shown by the Al-Al_3Ni alloy and discussed in the first progress report. Though there are some indications of such dimples (Fig. 2a), the extensive plastic deformation occurring during the fracture process probably distorted this simple pattern into a disordered array of mounds and troughs with Cr fibers generally associated with the mounds (Fig. 2b). It appears, therefore, that fracture of the Cr fibers serves as the initiation site for both the fibrous and shear failure modes.

The effect of varying fiber orientation on fracture mechanisms of the alloy was studied. As the shear process associated with failure for specimens oriented parallel to the growth direction involves rotation of the Cr fibers in the shear band to a position nearly parallel to the fracture plane, it was of interest to study the behavior of the alloy when the fibers were initially positioned parallel to a plane of maximum resolved shear stress. Two substandard tensile bars were machined at 45^{o} to the growth direction and tested. The resulting fracture mode was of the shear type. Electron fractography revealed that Cr fibers had nucleated the "elongated dimples" structure associated with shear failure (Fig. 3). Metallographic sections will be made to determine the relative position of the fracture plane and direction with respect to the position of the fibers in the sample.

Al-$CuAl_2$ System

Having successfully produced large grains of the Al-$CuAl_2$ eutectic, a group of microbend specimens were machined from one grain at specific angles in order to study the variation of strength with plate orientation. Seven circular discs whose surfaces were normal to the growth direction were cut from an ingot solidified at 2.05 cm/hr. Each disc was used to make one set of bend specimens wherein the length dimension of the sample made an angle of either zero, thirty, forty-five, sixty or ninety degrees with the plate direction (Fig. 4). Two discs were used for each of the sets containing plate orientations of zero and ninety degrees. By machining all samples from the same grain, the effect of crystallography on the mechanical behavior of specimens within each set was eliminated.

Test results, utilizing four-point loading, have been obtained for specimens with zero and ninety degree lamellar orientation. The data, Table I, indicate that the nominal outer fiber stress at fracture for lamellae oriented parallel to the test bar length was more than twice that for samples containing lamellae perpendicular to the length. The relative strengths of these specimens result from the presence of a maximum and a minimum amount of reinforcing by lamellae parallel and perpendicular, respectively, to the specimen length.

The data marked by asterisks in Table I indicate fracture strengths of specimens tested with the growth direction normal to the maximum stress surfaces, while the remaining data are for specimens which were positioned with the growth direction parallel to the maximum stress surfaces (Fig. 5). More data will be obtained before any definite conclusions are drawn concerning any change in mechanical behavior of either group as a function of the angle of rotation of the test bar about an axis parallel to the length dimension.

Light microscopy and electron fractography have established that for the case of lamellae parallel to the length dimension of the specimen, the Al platelets fail by plastic deformation while the $CuAl_2$ platelets cleave (Fig. 6). When the lamellae are normal to the test bar length dimension, the entire fracture surface appears to consist of cleaved $CuAl_2$ platelets (Fig. 7). Careful examination will be made to determine whether any interfacial decohesion had occurred along with the cleavage process.

Al-Al_3Ni

Metallographic sections were made in the region of the shoulder failures of those test specimens reported in the first progress report. One section revealed that there was no microstructural detail peculiar to the head end of the ingot which could be associated with the incipient fracture path. Careful examination of the unfailed shoulder of each test bar revealed the nucleation of one or more cracks. It is, therefore, felt that the shoulder failure was due to a stress concentration and/or load eccentricity and not to any microstructural detail found only at the head end of the ingot. In order to relieve the stress concentration, future tensile specimens will be machined with a more generous shoulder radius.

FUTURE WORK

During the next report period, work will continue on the following items:

1. Al-$CuAl_2$ microbend samples with lamellae oriented at thirty, forty-five and sixty degrees to the specimen length will be tested. In addition to calculation of maximum outer fiber strength, the elastic modulus of each sample will be obtained graphically and the modulus of the $CuAl_2$ phase obtained analytically.

2. Cu-Cr specimens will be prepared with Cr fibers oriented normal to the applied stress direction. Work will continue on the testing of individual Cr fibers and determining fiber size and spacing as a function of growth rate.

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2. Cu-Cr specimens will be prepared with Cr fibers oriented normal to the applied stress direction. Work will continue on the testing of individual Cr fibers and determining fiber size and spacing as a function of growth rate.

3. Tensile bars of the Al-Al_3Ni eutectic will be prepared with an increased shoulder radius and tested. Attempts will be made to determine the modulus of the alloy by ultrasonic techniques. Extracted fibers will be tested to obtain the strength and elastic properties of the Al_3Ni phase. These properties will be used in an attempt to mathematically predict the behavior of this material.

REFERENCES

1. Hertzberg, R. W., and R. W. Kraft: Fracture Mechanisms in Controlled Cu-Cr Eutectic Alloy. Accepted for publication in the Transactions of AIME.

2. Ford, J. A., and R. W. Hertzberg: Analytical and Experimental Investigations of the Fracture Mechanisms of Controlled Polyphase Alloys. Quarterly Progress Report No. 1, Navy, Bureau of Naval Weapons Contract N600(19)59361, February 1963.

TABLE I

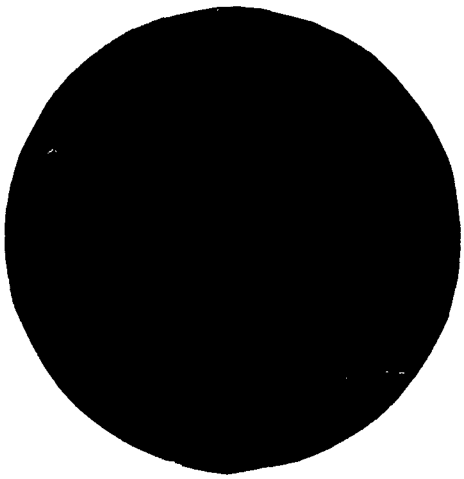
Outer Fiber Strength of Al-$CuAl_2$ Microbend Specimens

Lamellae Parallel to Specimen Length, Specimen Sets 6 and 7: Sample Number	Strength	Lamellae Perpendicular to Specimen Length, Specimen Set 1: Sample Number	Strength
63-268-02-6a	42,300	63-268-02-1a	19,700
63-268-02-6b	44,900	63-268-02-1b	17,500
63-268-02-6c	47,600*	63-268-02-1c	33,900
63-268-02-7a	47,400	63-268-02-1d	26,700*
63-268-02-7b	47,600	63-268-02-1e	16,700*
63-268-02-7c	49,800*		
63-268-02-7d	47,700*		
σ avg = 46,800		σ avg = 22,900	

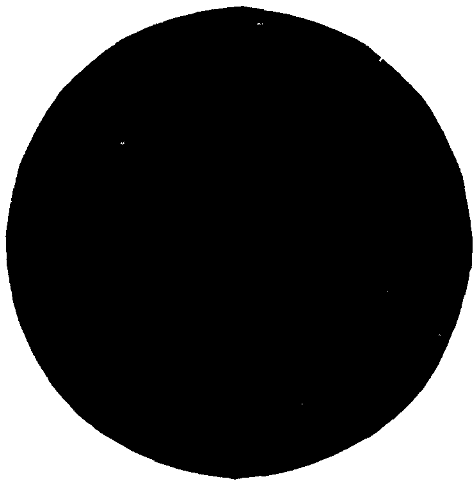
* Specimens tested with growth direction normal to maximum stress surface.

COMPARISON BETWEEN AS-CAST AND UNIDIRECTIONALLY SOLIDIFIED INGOTS

MAGNIFICATION: 2X



AS-CAST



UNIDIRECTIONALLY SOLIDIFIED

ELECTRON FRACTOGRAPHS OF TENSILE MODE OF FAILURE IN Cu-Cr ALLOY

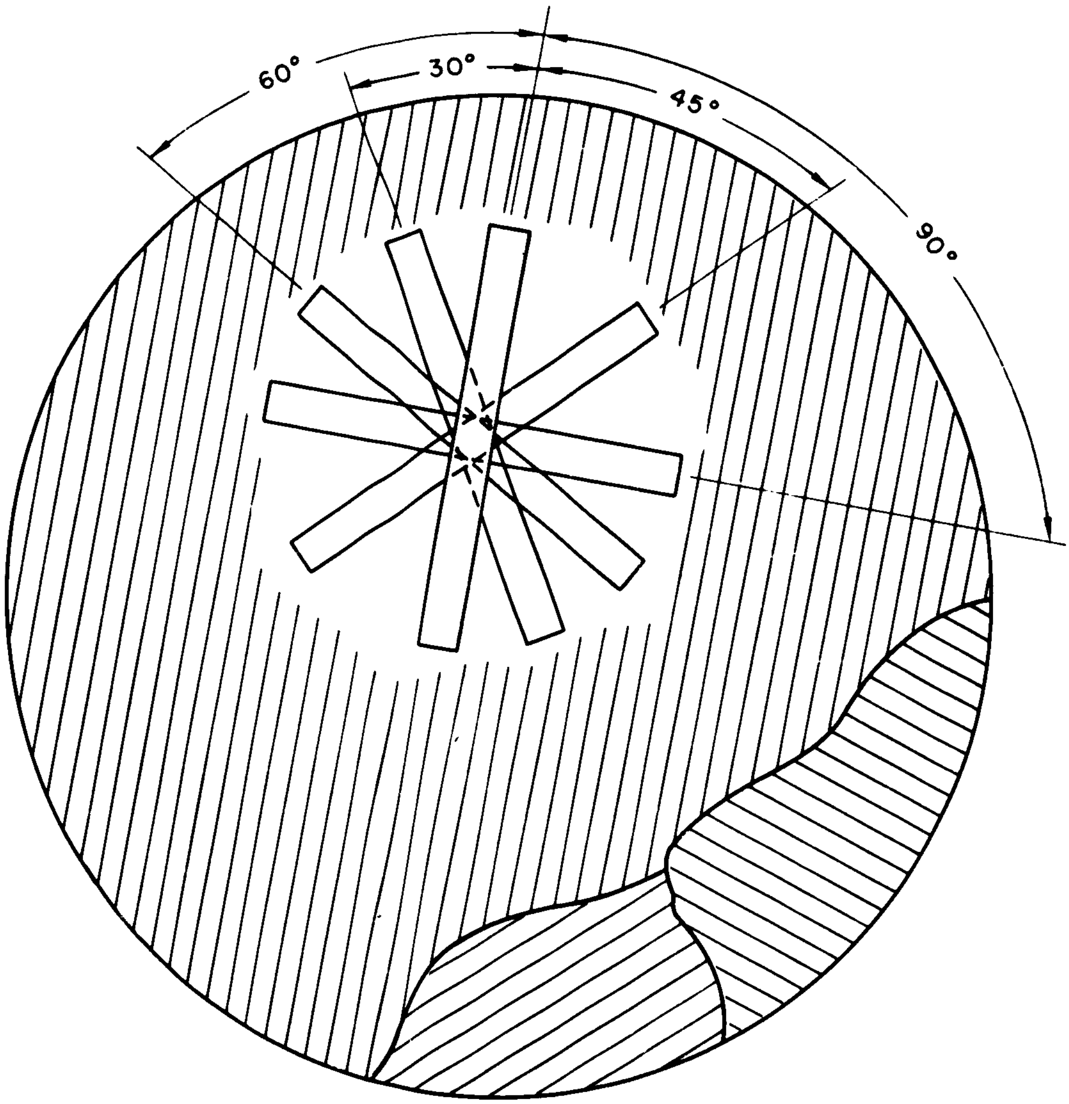
a) WHISKERS ASSOCIATED WITH EQUIAXED DIMPLES
MAGNIFICATION: 15,600 X

b) DISTORTED ARRAY OF MOUNDS AND TROUGHS.
Cr FIBERS GENERALLY ASSOCIATED WITH MOUNDS
MAGNIFICATION: 6000X

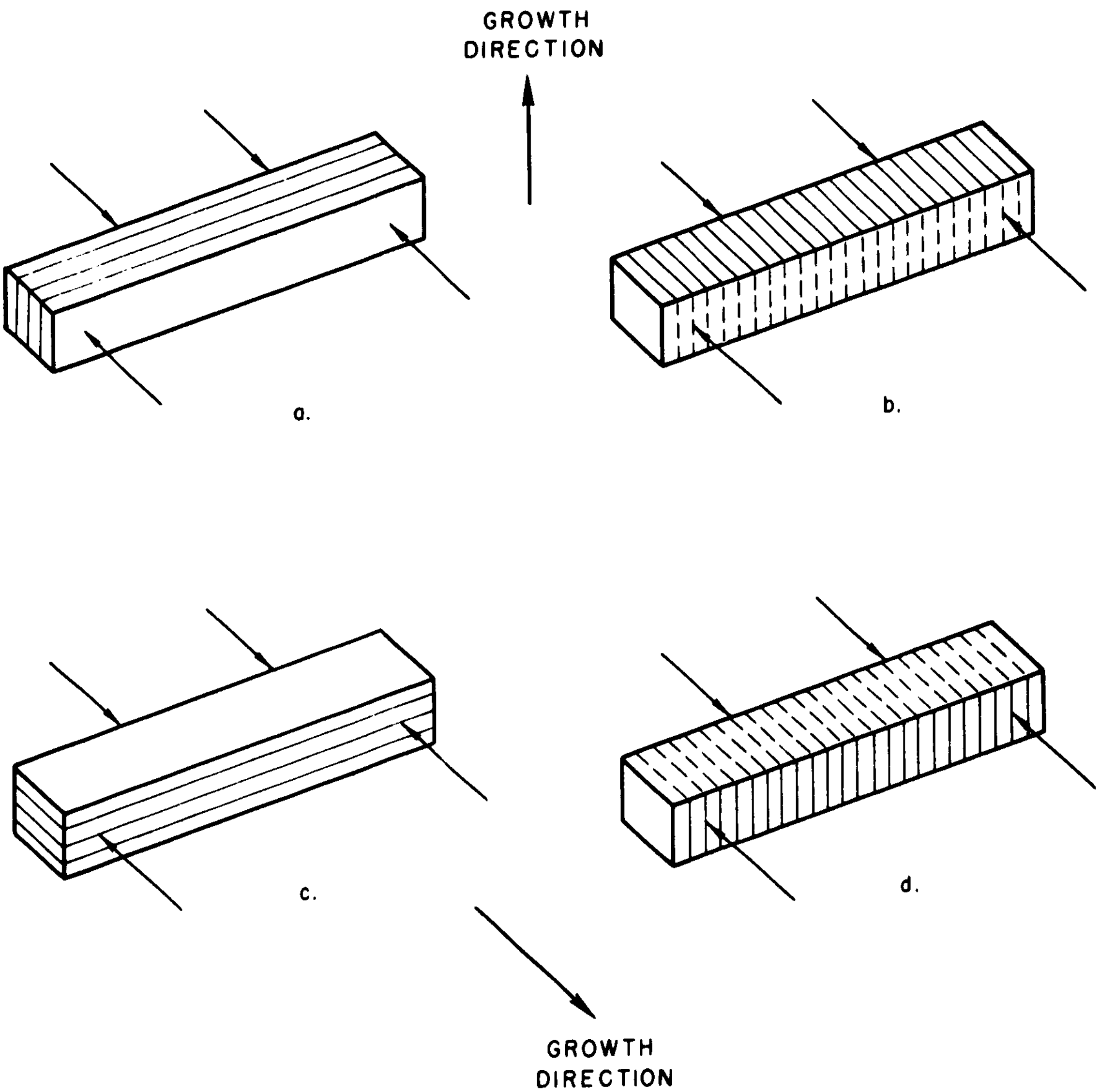
"ELONGATED DIMPLE" STRUCTURE ON FRACTURE SURFACE.
SPECIMEN PREPARED AT 45 DEGREES
TO GROWTH DIRECTION

MAGNIFICATION: 8600 X

SCHEMATIC ILLUSTRATING RELATION OF MICROBEND SPECIMENS TO LAMALLAE ORIENTATION IN Al - $CuAl_2$ EUTECTIC

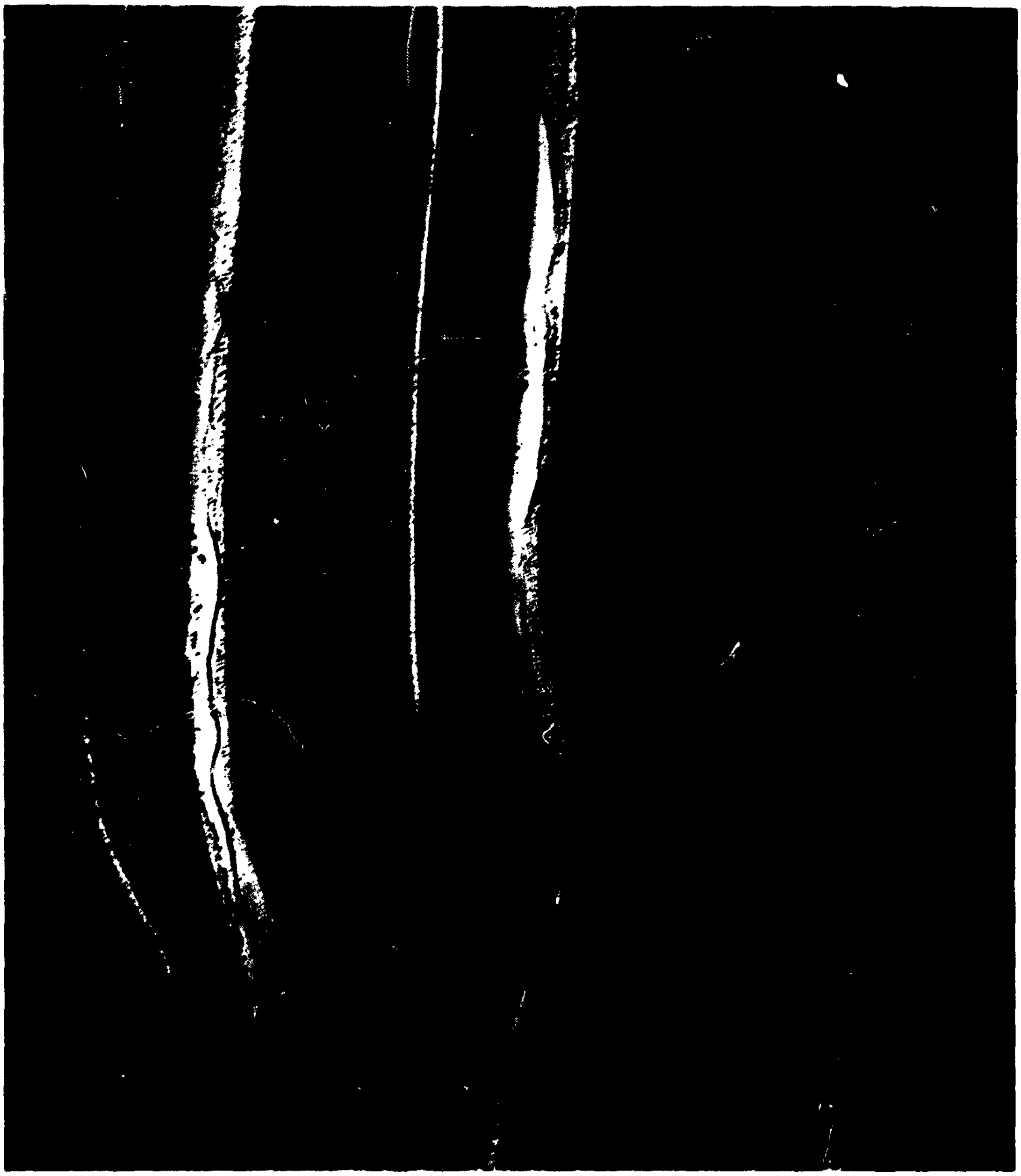


SCHEMATIC OF LAMALLAE LOAD RELATIONSHIPS IN MICROBEND TESTS



FRACTURE SURFACE OF Al-$CuAl_2$ ALLOY ILLUSTRATING CLEAVAGE OF $CuAl_2$ AND DUCTILE FAILURE OF Al

MAGNIFICATION: 14,800 X



FRACTURE SURFACE OF Al-$CuAl_2$ ALLOY ILLUSTRATING CLEAVAGE OF $CuAl_2$ PLATELETS

MAGNIFICATION: 110 X

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